Increased Variability in the Early Winter Subarctic North American Atmospheric Circulation*

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ABSTRACT

The last decade shows increased variability in the Arctic Oscillation (AO) index for December. Over eastern North America such increased variability depended on amplification of the climatological longwave atmospheric circulation pattern. Recent negative magnitudes of the AO have increased geopotential thickness west of Greenland and cold weather in the central and eastern United States. Although the increased variance in the AO is statistically significant based on 9-yr running standard deviations from 1950 to 2014, one cannot necessarily robustly attribute the increase to steady changes in external sources (sea temperatures, sea ice) rather than a chaotic view of internal atmospheric variability; this is due to a relatively short record and a review of associated atmospheric dynamics. Although chaotic internal variability dominates the dynamics of atmospheric circulation, Arctic thermodynamic influence can reinforce the regional geopotential height pattern. Such reinforcement suggests a conditional or state dependence on whether an Arctic influence will impact subarctic severe weather, based on different circulation regimes. A key conclusion is the importance of recent variability over potential trends in Arctic and subarctic atmospheric circulation. Continued thermodynamic Arctic changes are suggested as a Bayesian prior leading to a probabilistic approach for potential subarctic weather linkages and the potential for improving seasonal forecasts.

1. Introduction

Several authors have commented on major individual negative Arctic Oscillation (AO) events in recent years that were associated with severe cold temperatures in midlatitudes over North America and parts of Europe (Cattiaux et al. 2010; L’Heureux et al. 2010). Single large January negative AO in 2010 and positive AO in 2012 events were discussed by Santos et al. (2013). L’Heureux et al. (2010) note the largest negative AO event during 2009 in a 60-yr record. Although by definition, the AO is the first empirical orthogonal function of sea level pressure in the Northern Hemisphere 20°–90°N (Thompson and Wallace 1998), the AO index only broadly represents the more complex northern latitude atmospheric circulation. Very large positive values of the AO do, however, indicate zonal flow and large negative values suggest increased meridional circulation with ties to cold air advection into midlatitude North America (Thompson and Wallace 2000; also see http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml). We further address such extreme cases specific to the last decade over eastern North America (2006–14).

We make the case that the last decade shows the most variability in AO extremes for December since 1950. Figure 1 show the 9-yr running means (red curves in the top panels) and standard deviations (SD, the blue curves in the bottom panels) of the AO for early winter months (November–January). Results are similar for 7- or 11-yr periods; 9 years provides temporal resolution and retains a minimum number of degrees of freedom. Large
AO magnitudes in December are limited to years after 2000. The magnitudes of the AO and its SD for November are considerably smaller than the other two months (except for two extreme cases) suggesting that the strength of the winter Northern Hemisphere atmospheric circulation is not completely established until December. January shows large AO magnitudes throughout the record beginning in 1950.

Although the increased variance in the AO in recent Decembers is statistically different from random at a 95% significance level based on 9-yr boxcar average standard deviations over a period from 1950 to 2014, one cannot necessarily robustly attribute the increase to causes other than a chaotic view of internal atmospheric variability, such as steady changes from an external source [sea surface temperatures (SST), sea ice]. This is due to a relatively short record, a single occurrence (December), and a review of associated atmospheric dynamics. For example, the early 1990s had a run of positive AO values that were suggested at the time as a global warming signal (Feldstein 2002); these positive values were replaced by a period of early winter variability (Overland and Wang 2005; Table 1 in this paper). The same is true for the time series for the North Atlantic Oscillation (NAO); a projected downward trend since 1990 (Wang et al. 2010) is better interpreted as variability (Hall et al. 2015). Other studies can show that trends in extreme events are often not significant (Screen and Simmonds 2013). To summarize, with regard to climate variations, Trenberth (2011) and Shepherd (2014) note that thermodynamic aspects of change (temperature, water vapor, sea ice) tend to be robust, while dynamic aspects are not so robust. For atmospheric circulation, chaotic internal variability dominates over multiple external sources.

**Fig. 1.** (top) November, December, and January monthly Arctic Oscillation (AO) index and 9-yr running mean (red), and (bottom) running standard deviation (SD, blue). The horizontal line is the mean for the record. The data are from http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml.
and the composite height anomaly patterns for the three recent major negative AO (−AO) events (2009, 2010, 2012) and three positive AO (+AO) events (2006, 2011, 2013) are presented in Figs. 2b and 2c. The positive geopotential height anomalies for −AO cover a substantial region centered west of Greenland (Fig. 2b), collocated with the minimum height center of the climatology. The magnitudes of the negative height anomalies for +AO are less than the positive anomalies for −AO and are centered east of Greenland (Fig. 2c). As expected, westerly winds over the northern midlatitudes are decreased in the −AO cases and increased with a +AO in a zonal pattern from the Pacific across to Europe. Especially for the −AO events, the anomaly pattern can be considered a change in amplitude of the existing climatological North American circulation pattern. Neither phase of the AO nor their associated circulation patterns dominate the recent or long-term record.

Given the near-Greenland location of the AO associated geopotential height anomaly patterns, an additional regional index is the normalized Greenland blocking index (GBI; Table 1), defined as 500-hPa geopotential heights averaged over the domain, 60°–80°N and 80°–20°W (Hanna et al. 2013). The December–January AO/GBI correlation for 1950–2014 is −0.86 (Table 1). Although recent Decembers and Januaries contain record AO and GBI values, we cannot show that the mean AO for the last nine Decembers is statistically different from random at a 95% significance level relative to the 1950–2014 time series, based on 9-yr boxcar averages. The recent 9-yr SD for the AO is statistically significant. The −AO cases can be considered as an amplified “wavy” circulation pattern over North America; Fig. 2d maps the 700-hPa meridional wind component for a December 2009, 2010, and 2012 composite; blue shading indicates winds coming from the north extending into the southeastern United States.

The difference in monthly mean near-surface temperatures between the three −AO minus the +AO cases is greater than 4°C for northeastern Canada (positive) and central Canada and the southeastern United States (negative; Fig. 3a). Cold temperatures in the southeastern United States in these −AO cases lead to much discussion on the impact of the wave amplitude of the “polar vortex.” Such a −AO feature is consistent with the positive temperature anomalies observed at the northwest Greenland weather station at Upernavik (Hanna et al. 2013). The composite 500–1000-hPa geopotential thickness anomaly field for the three −AO minus +AO cases has major positive values over Baffin Bay and Davis Strait (Fig. 3b) consistent with a low-level contribution to the −AO positive geopotential height anomaly in Fig. 2b.

Table 1. Monthly AO and GBI index during 2006–14 for winter months. When the positive GBI is greater than one standard deviation, the numbers are shown in bold, the same is true for negative AO. When the negative GBI (or positive AO) is greater than one standard deviation, numbers are shown in italic. The year on the far right column indicates the corresponding January to its left.

<table>
<thead>
<tr>
<th>Year</th>
<th>Nov AO</th>
<th>GBI</th>
<th>Dec AO</th>
<th>GBI</th>
<th>Jan AO</th>
<th>GBI</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.7</td>
<td>−0.5</td>
<td>2.5</td>
<td>−0.7</td>
<td>2.4</td>
<td>−0.1</td>
</tr>
<tr>
<td>2007</td>
<td>−0.4</td>
<td>0.2</td>
<td>1.0</td>
<td>−1.1</td>
<td>1.2</td>
<td>−0.4</td>
</tr>
<tr>
<td>2008</td>
<td>0.2</td>
<td>0.5</td>
<td>0.9</td>
<td>−0.7</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>2009</td>
<td>0.6</td>
<td>−0.1</td>
<td>−3.2</td>
<td>2.8</td>
<td>−2.2</td>
<td>2.1</td>
</tr>
<tr>
<td>2010</td>
<td>0.3</td>
<td>1.9</td>
<td>−2.4</td>
<td>3.6</td>
<td>−1.3</td>
<td>1.6</td>
</tr>
<tr>
<td>2011</td>
<td>1.6</td>
<td>−0.6</td>
<td>2.4</td>
<td>−1.9</td>
<td>0.2</td>
<td>−0.4</td>
</tr>
<tr>
<td>2012</td>
<td>−0.01</td>
<td>0.2</td>
<td>−1.6</td>
<td>1.6</td>
<td>−0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>2013</td>
<td>2.1</td>
<td>−1.0</td>
<td>1.7</td>
<td>−1.4</td>
<td>−0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>2014</td>
<td>−0.4</td>
<td>0.01</td>
<td>0.6</td>
<td>−0.6</td>
<td>1.5</td>
<td>−1.5</td>
</tr>
</tbody>
</table>

Although the AO is a single Arctic-wide atmospheric index, of interest are associated circulation anomalies over North America and their connection to atmospheric conditions in northeastern Canada and near Greenland in recent years. While the variability in the sign of the AO is most likely a result of atmospheric internal variability (chaotic flow and longwave persistence) (Woollings et al. 2010; Hanna et al. 2015), the magnitude of negative AO events may include contributions from a combination of midlatitude/tropical teleconnections forced by SST and lower-tropospheric Arctic temperature anomalies in some years but not others (Ding et al. 2014; Hanna et al. 2015; Perlwitz et al. 2015; Overland et al. 2015). The composite 500–1000-hPa geopotential height anomaly field for the three −AO events has major positive values over Baffin Bay and Davis Strait consistent with a low-level contribution to the −AO positive geopotential height anomaly in Fig. 2b.
3. Discussion

Recent review papers motivate the present contribution: potential Arctic impacts on midlatitude weather would be regional and episodic due to a combination of atmospheric circulation internal variability, lower-tropospheric temperature anomalies, and midlatitude teleconnections (Cohen et al. 2014; Kim et al. 2014; Barnes and Screen 2015; Overland et al. 2015). Shepherd (2014) and Trenberth et al. (2015) proposed that potential impacts from SST (or Arctic external sources) on subarctic and midlatitude atmospheric circulation are conditional or state dependent. For example strong zonal flow of $+\text{AO}$ may not be sensitive to further modification by boundary conditions, but $-\text{AO}$ is regionally sensitive. This nonlinear response of the amplification of the circulation regime would be difficult to determine with linear statistics.

Because of large internal atmospheric variability, one would not expect to necessarily have the same AO or midlatitude circulation response every year from similar or trending external sources, such as tropical and Pacific SST or regional Arctic temperature increases, sea ice loss, and changes in snow cover. Model studies can show either an Arctic/midlatitude linkage or no effect based on different ensemble members with the same initial conditions (Orsolini et al. 2012; Screen et al. 2014; Shepherd 2014). Any potential linkage of direct or indirect forcing to the longwave atmospheric circulation would represent a small signal in large background variability (Sokolova et al. 2007; Strey et al. 2010; Balmaseda et al. 2010; Hopsch et al. 2012; Liu et al. 2012; Rinke et al. 2013; Tang et al. 2013).

Ding et al. (2014) and Perlwitz et al. (2015) propose that Arctic temperature increases, especially in the northeastern Canadian and Greenland regions, result from internal variability, a direct Arctic source contribution, and impact from tropical and extratropical Pacific SST anomalies. Large positive SST anomalies in the North Pacific in winters 2013–14 and 2014–15 helped establish an amplified ridge–trough height field.
FIG. 3. (a) Composite of near-surface (1000 hPa) air temperature anomalies (°C), (b) 1000–500-hPa geopotential thickness (m), and (c) NCEP surface skin temperature anomalies for three −AO Decembers (2009, 2010, and 2012) minus three +AO Decembers (2006, 2011, and 2013). Maximum near-surface temperature anomalies over Baffin Bay and Hudson Bay are in excess of +4°C.
over North America, with a tropical teleconnection (Lee et al. 2015; Hartmann 2015). Lee et al. conclude that the magnitude of the SST and sea ice influence was unique in boreal winter 2013–14 and had a weaker contribution in the winters of 2010–11 and 2012–13, our negative AO years.

Further understanding of the maintenance of regional features comes from a qualitative interpretation of the geopotential tendency equation in pressure coordinates [from http://snowball.millersville.edu/~ademaria/ESCI343/esci343_lesson02_QG_tendency_eqn.pdf, which is a modified version of Eq. (6.14) from Holton (1979)]:

\[- \frac{\partial \Phi}{\partial t} = -f_0 \mathbf{V}_g \cdot \nabla \Phi + f_0 \frac{\partial}{\partial \sigma} \left( \frac{1}{\sigma} \nabla \Phi \right) - \frac{f_0^2}{\sigma} \frac{\partial}{\partial p} \left( \nabla \cdot \nabla \Phi \right) - \frac{f_0^2 R_d}{\sigma C_p} \frac{\partial}{\partial p} \left( \frac{dQ/dt}{p} \right),\]

(A) (B) (C)

where \( \chi = \partial \Phi / \partial t \) is defined as the geopotential tendency and the static-stability parameter \( \sigma \) is defined as \( \sigma = -(\alpha / \theta)(\partial \theta / \partial p) \), where \( \theta \) is potential temperature, \( \alpha \) is specific volume, \( \Phi \) denotes the geopotential height, \( f(f_0) \) is the Coriolis parameter (at 45°), \( \mathbf{V}_g \) is the geostrophic wind, \( R_d \) is the gas constant for dry air, \( C_p \) is the specific heat constant pressure, and \( Q \) is the external heating.

This equation illustrates that the geopotential height rises are proportional to negative vorticity advection (A) and a decrease with height of thickness advection (B) and heating (C). Midlevel geopotential heights will rise with low-level warm advection and low-level heating. Note that the equation is a proportionality rather than an equality and that quantitative calculation of the right-hand side of the equation involves gradients and products that are difficult to assess from reanalysis products. However, following Holton’s review we can qualitatively interpret the terms by inspection of the relevant fields. Low-level warm advection is suggested by 700-hPa southerly winds in Baffin Bay (Fig. 2d) combined with the thickness maximum in Fig. 3b; this advection would be seen after such a positive GBI pattern was established. Even though positive temperature anomalies decreased with height from 925 to 500 hPa over the greater northern Baffin Bay region for the composite of the three −AO cases (Fig. 4), a potential contribution to term B, the location of the main temperature anomaly maximum is seen at all levels suggesting that the main contribution is from dynamics (term A).

Further, low-level heating is suggested from the anomaly of the National Centers of Environmental Prediction (NCEP) surface skin temperature field for the December −AO minus +AO cases (Fig. 3c); maximums are over Baffin Bay and Hudson Bay in excess of +5°C. The surface temperature of sea ice is determined from an energy balance that includes the surface heat fluxes and the heat capacity of the ice (W. Ebisuzaki, NCEP, 2014, personal communication). These temperature maximum regions had less sea ice in October during the −AO years (National Snow and Ice Data Center analyses). Low-level positive temperature anomalies contributed to geopotential height changes over an extended region in recent negative AO years (see Serreze et al. 2011, for other examples). To summarize, low-level Arctic processes were involved in amplifying the existing longwave pattern over eastern North America in some years but not others.

4. Summary

A key conclusion is the importance of recent variability rather than trends in Arctic and subarctic atmospheric circulation, especially on a regional basis. The recent variability in the AO and GBI were associated with increased geopotential thickness west of Greenland and major eastern North American cold events in some years. Although the recent decade Decembers show a statistical increase in the variance of the AO, we cannot robustly attribute them to external sources rather than a chaotic view of internal variability (Barnes 2013; Screen and Simmonds 2013; Francis and Vavrus 2015; Lee et al. 2015). Data support the hypothesis that such variability depends on amplification of the existing climatological North American longwave pattern. If there is an Arctic influence, it reinforces the height field west of Greenland in years with a negative AO pattern, established by random circulation instabilities and by midlatitude teleconnections. We extend the conclusion of Shepherd (2014) and Trenberth et al. (2015) that the occurrence of midlatitude atmospheric circulation regimes is largely unaffected by climate or Arctic change, with the question being whether known changes in the thermodynamic state affect the amplitude of a particular event. We note that Arctic/midlatitude connections may be conditional or state dependent on the circulation type, further complicating exploration of linkages.
There is potential for improving seasonal forecasts through further understanding of multiple external sources and teleconnections influencing subarctic atmospheric circulation (Jung et al. 2014). A Bayesian approach would formulate increasing thermodynamic “Arctic change” as a prior and establish the extreme event problem on a probabilistic and no-regrets risk avoidance basis. As noted by Trenberth (2011, p. 927): “Sources of uncertainty in the observational record or models should not be preferentially assigned toward underestimating the human (or Arctic change) component.”

One should consider future emergence of Arctic change on midlatitude weather as an important research challenge, but one that is difficult to establish (Barnes and Screen 2015). At this point, one should include equatorial and Pacific teleconnections and random variability as hypotheses for contributing to future subarctic/midlatitude extreme events and not exclude possible Arctic reinforcement mechanisms (Deser et al. 2010; Hopsch et al. 2012; Jaiser et al. 2012; Tang et al. 2013; Palmer 2014). Perlwitz et al. (2015) and Lee et al. (2015) suggest that all factors have important but small contributions.

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